

# Morphological and photometric evolution of ultra-luminous infrared galaxies: Nature of faint SCUBA sources

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## ABSTRACT

We investigate when and how a dusty starburst galaxy merger can be heavily obscured by dust and consequently becomes an ultra-luminous infrared galaxy (ULIRG), based on numerical simulations of chemodynamical and photometric evolution of dusty gas-rich major galaxy mergers. We found that a major galaxy merger is more likely to become an ULIRG preferentially in the merger late phase, when the two disks become very close and the very high-density dusty gas can obscure heavily the central secondary massive starburst. We furthermore show how the optical and near-infrared morphology of a simulated ULIRG at intermediate ( $z=0.4$ ) and high redshift ( $z=1-2$ ) can be observed by the Hubble Space Telescope (HST) in order to present a plausible explanation for the origin of some host galaxies of the faint SCUBA sources recently observed by Smail et al. (1998). The results of our numerical simulations imply that some SCUBA sources with apparently faint and compact HST morphology can be higher redshift dust-enshrouded starburst mergers with their outer low surface brightness tidal features hardly detectable in the present optics of the HST.

*Subject headings:* galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: ISM – galaxies: infrared – galaxies: interaction – galaxies: structure

## 1. Introduction

Recent observational studies with the Sub-millimeter Common-User Bolometer Array (SCUBA) (Holland et al. 1999) on the James Clerk Maxwell Telescope have revealed possible candidates of heavily dust-enshrouded starburst galaxies at intermediate and high redshift, which could be counterparts of low redshift ultra-luminous infrared galaxies (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Smail et al. 1998; Barger et al. 1999; Lilly et al. 1999). Although optical morphology of these sub-millimeter galactic sources should be treated with caution owing to the absence of high resolution sub-mm imaging capability (Richards 1999), more than 50 % of those are suggested to show the indication of galactic interaction and merging (Smail et al. 1998). The huge amount of molecular gas ( $\sim 5 \times 10^{10} M_{\odot}$ ) derived from CO emission and the inferred large star formation rate ( $\sim 10^3 M_{\odot} \text{yr}^{-1}$ ) in a few sub-millimeter extragalactic sources (e.g. SMMJ14011+0252) are suggested to be consistent with the scenario that the formation of some intermediate and high redshift elliptical galaxies is associated with galaxy mergers with their starburst activities heavily hidden by dust extinction (Frayser et al. 1998; Frayer et al. 1999). Furthermore observational studies of an extremely red object ERO J 164502-4626.4 (HR 10) with the redshift of 1.44 by the Hubble Space Telescope and the SCUBA have found that this high redshift galaxy is also a dust-enshrouded starburst galaxy with clear indication of galaxy merging/interaction (Graham & Dey 1996; Cimatti et al. 1998; Dey et al. 1998).

Although low redshift ultra-luminous infrared galaxies (ULIRG) are generally considered to be ongoing galaxy mergers with the triggered prominent nuclear activities (starburst or AGN) heavily obscured by dust (Sanders et al. 1988; Sanders & Mirabel 1996), the origin of the faint SCUBA sources is not so clearly understood. In this Letter, we numerically investigate both morphological and photometric properties of dusty starburst galaxy mergers in an explicitly self-consistent manner and thereby demonstrate when and

how a gas-rich merger between two spirals becomes an ULIRG. We particularly discuss the origin of very faint and compact HST optical morphology of possible host galaxies of some faint SCUBA sources recently revealed by Smail et al. (1998) by demonstrating how intermediate and high redshift dust-enshrouded starburst galaxies can be seen by the HST WFPC2 and NICMOS (NIC2).

## 2. Model

The most remarkable difference in investigating photometric evolution of dusty galaxies between the present model and previous one-zone models (e.g., Mazzei, Xu, & De Zotti 1992; Franceschini et al. 1994; Guiderdoni et al. 1998) is that we derive spectral energy distribution (SED) of galaxies based on the result of numerical simulations that can follow both dynamical and chemical evolution of galaxies. The numerical techniques for solving galactic chemodynamical and photometric evolution are given in Bekki & Shioya (1999a,b), and accordingly we describe only briefly the present numerical model of dusty starburst galaxy mergers here. We construct models of galaxy mergers between gas-rich disk galaxies with equal mass by using Fall-Efstathiou model (1980). The total mass and the size of a progenitor disk are  $6.0 \times 10^{10} M_{\odot}$  and 17.5 kpc, respectively. The collisional and dissipative nature of the interstellar medium with the initial total mass equal to  $3.0 \times 10^{10} M_{\odot}$  is modeled by the sticky particle method (Schwarz 1981). Star formation is modeled by converting the collisional gas particles into collisionless new stellar particles according to the Schmidt law (Schmidt 1959) with the exponent of 2.0. Chemical enrichment through star formation during galaxy merging is assumed to proceed both locally and instantaneously in the present study. The fraction of gas returned to interstellar medium in each stellar particle and the chemical yield are 0.2 and 0.03, respectively. Initial metallicity  $Z_*$  for each stellar and gaseous particle in a given galactic radius  $R$  (kpc) from the center of a disk is

given according to the observed relation  $Z_* = 0.06 \times 10^{-0.197 \times (R/3.5)}$  of typical late-type disk galaxies (e.g., Zaritsky, Kennicutt, & Huchra 1994). Mean ages of old stellar components initially in a merger progenitor disk at the redshift  $z=0.4$ ,  $1.0$ , and  $1.5$  are assumed to be  $7.14$ ,  $3.80$ , and  $2.46$  Gyr, respectively. The orbital plane of a galaxy merger is assumed to be the same as  $x$ - $y$  plane and the initial distance between the center of mass of merger progenitor disks is  $140$  kpc. Two disks in the merger are assumed to encounter each other parabolically with the pericentric distance of  $17.5$  kpc.

It is assumed in the present study that the SED of a model galaxy is a sum of the SED of stellar particles. We first calculate dust extinction of star light for *each* stellar particle and dust temperature for *each* gaseous particle, based on the three dimensional spacial distribution of stellar and gaseous particles. We then sum each stellar particle's SED corrected by dust extinction and the dust re-emission of each gaseous particle. The method to derive the dust extinction and re-emission for each particle is described as follows. Absorption of star light of a stellar particle is modeled according to the following reddening formulation (Black 1987; Mazzei et al. 1992);  $E(B-V) = N(H)/4.77 \times 10^{21} \text{cm}^{-2} \times (Z_g/0.02)$ , where  $N(H)$  and  $Z_g$  are gaseous column density and gaseous metallicity, respectively. Using the derived reddening  $E(B-V)$  and extinction law by Cardelli et al. (1989), we adopt the so-called screen model and calculate the absorption of the stellar particle. By assuming the modified black body radiation with the emissivity ( $\epsilon$ ) law  $\epsilon \propto \nu^2$ , we determine the dust temperature of a gas particle such that total energy flux of dust absorption is equal to that of dust re-emission. We here do not include the albedo for dust grains, which means that only stars and new stars heat dust. For calculating the SED of each stellar particle with a given age and metallicity, we use the spectral library GISSSEL96 which is the latest version of Bruzual & Charlot (1993). Using the derived SED, we investigate how dust-enshrouded starburst galaxy mergers at  $z=0.4$ ,  $1.0$ , and  $1.5$  can be seen in the HST. The method to construct the synthesized HST images of galactic morphology in the present study is

basically the same as that described by Mihos (1995). In the followings, the cosmological parameters  $H_0$  and  $q_0$  are set to be  $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and 0.5 respectively.

EDITOR: PLACE FIGURE 1 HERE.

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### 3. Result

Figure 1 and 2 describe the time evolution of star formation rate and the rest-frame SED in a dusty gas-rich major galaxy merger at  $z=1.0$  and the mass distribution of stellar and gaseous components of the merger at the epoch of the maximum secondary starburst,  $T = 1.3 \text{ Gyr}$ , respectively. From now on, the time  $T$  represents the time that has elapsed since the two disks begin to merge at each redshift. As is shown in Figure 1, star formation rate in the present prograde-retrograde merger becomes maximum ( $\sim 378 M_\odot/\text{yr}$ ) at  $T = 1.3 \text{ Gyr}$ , when two disks of the merger become very close to suffer from final violent relaxation. These results are qualitatively consistent with those in Mihos & Hernquist (1996). The SED at  $T = 1.3 \text{ Gyr}$  in Figure 1 is rather similar to the observed SED of typical ULIRGs, which implies that the present dusty starburst merger model can be observed as an ULIRG in the late of galaxy merging. The SED of a dusty merger depends on encounter parameters in such a way that a prograde-retrograde merger shows stronger infrared re-emission in the merger late phase than prograde-prograde one (Bekki & Shioya 1999b).

Figure 2 shows that both new stars and gas are more centrally concentrated than old stellar components, which means that star light from new stars formed by secondary massive starburst are more heavily obscured by dusty interstellar medium than that of old stellar components. These results in Figure 1 and 2 clearly demonstrate that starburst population in the merger is very heavily obscured by dusty interstellar medium ( $A_V \sim 2.46$  mag) and consequently the dust re-emission in far-infrared ranges becomes very strong at the maximum starburst ( $L_{IR} = 1.59 \times 10^{12} L_{\odot}$ ). The reasons for this heavy dust extinction are firstly that column density of dusty interstellar medium becomes extremely high owing to the strong central accumulation of gas and secondly that the central gaseous metallicity, which is a measure of total amount of dust, also becomes rather large ( $\sim 0.04$ ) because of efficient and rapid chemical evolution in galaxy merging with secondary starburst. The galaxy merger 0.05 Gyr before and after the maximum starburst does not show the SED characteristics of ULIRGs, which suggests that the time-scale during which the merger remnant can be observed as an ULIRG is very short (less than 0.1 Gyr). Owing to the heavy dust extinction, the merger shows very red rest-frame color  $V - I = 0.97$  for a starburst galaxy.

Figure 3 shows how the optical and near-infrared morphology of this ULIRG merger at  $T = 1.3$  Gyr can be observed by the HST WFPC2 and NICMOS if it locates at the redshift  $z=0.4$ , 1.0, and 1.5 (See also Figure 2 for the raw image of the merger). Outer diffuse large arc-like structure composed mainly of old stars, which is discernibly seen in the upper left part of Figure 2, can not be seen even in the merger at  $z=0.4$ . Tidal feature indicative of major galaxy merging can be discernibly seen at  $z=0.4$  and can not be seen at all at  $z=1.0$  and 1.5. The faint and compact morphology of the present merger remnant at  $z=1.0$  and 1.5 is similar to some possible faint optical counterparts of the first SCUBA sources observed by Smail et al. (1998). We furthermore stress that it is hard to observe the tidal feature even in the HST image with the exposure time equal to  $1.24 \times 10^5$  sec

corresponding to that for the Hubble Deep Field (HDF). These results imply that it is not so easy task to clarify the origin of high redshift ULIRGs ( $z > 1$ ) solely by optical and near-infrared HST morphological studies; If the formation of high redshift ULIRGs is closely associated with major galaxy merging, even the deepest existing HST surveys have some difficulties in proving that. The  $850\ \mu\text{m}$  sub-millimeter energy flux of the ULIRG merger is found to be 10.85 mJy for  $z=1.0$  and 2.36 mJy for  $z=1.5$ . Considering the flux value of the merger at  $z=1.0$  and 1.5 exceeding the observed SCUBA flux  $2.1 - 7.0$  mJy by Hughes et al. (1998) and  $3.3 - 4.6$  by Barger et al. (1998) and faint compact morphology of the merger, a high redshift dust-enshrouded starburst merger ( $z \sim 1.0$ ) can be observed as a very compact SCUBA source. Furthermore the apparently compact remnant shows very red  $R - K$  color (4.70 mag for  $z=1.0$  and 4.86 for  $z=1.5$ ) for its  $K$  band magnitude (21.26 mag for  $z=1.0$  and 22.42 for  $z=1.5$ ), which implies an evolutionary link between dusty mergers and the high redshift extremely red objects (EROs). The present model describes the detectability of only *one* merger model with the initial disk mass  $M_d = 6.0 \times 10^{10} M_\odot$  in the *present* optics of the HST. Accordingly we must stress that the detectability of tidal feature of a high redshift ULIRG in the HST can depend on mass and luminosity of a merger and furthermore that the future improved HST Advanced Camera for Surveys (ACS) is expected to reveal the more detailed morphology of a high redshift ULIRG.

#### 4. Discussion and conclusion

Our numerical results have demonstrated that a dust-enshrouded starburst merger can be observed as a SCUBA source with faint and compact morphology at high redshift. The present results furthermore provide clues to the understanding of the evolutionary link between the extremely red objects ‘ERO’ (e.g., Elston, Rieke, & Rieke 1988) and the present day elliptical galaxies. Recent observational studies have revealed that ERO J



164502+4626.4 (HR 10) is not a red elliptical galaxy passively evolving at high redshift but a dust-enshrouded starburst galaxy at redshift  $z=1.44$  (Cimatti et al. 1998; Dey et al. 1998). Peculiar morphological properties in rest-frame far-red and near-UV range, the large  $850\ \mu\text{m}$  energy flux, and the inferred huge star formation rate in this HR 10 are qualitatively consistent with the present numerical results of dusty starburst mergers, which implies that *some* EROs are dusty starburst major mergers and thus evolve eventually into the present-day elliptical galaxies. Then, what fraction of the present-day ellipticals have experienced the past dusty ERO phase ? Considering both the very short time-scale (less than 0.1 Gyr in the present study) during which dusty mergers can be identified as EROs and the high surface density of EROs ( $0.14\ \text{arcmin}^{-2}$  for EROs with  $R - K \geq 6$  and  $K \leq 19.75$ ) derived by Beckwith et al. (1998), the discovery of the possible dusty starburst galaxy merger HR 10 implies that the fraction is likely to be fairly large. Furthermore, the increase of number fraction of apparently interacting/merging galaxies with redshift in the HDF (Driver et al. 1998), the very small fraction (less than 8 %) of early-type E/S0 galaxies in the HDF (Marleau & Simard 1998), and the observed high surface density of EROs (Beckwith et al. 1998; Dey et al. 1998) combine to motivate us to interpret that a sizable fraction of the present-day elliptical galaxies were previously ongoing major mergers with dusty starburst at intermediate and high redshift. However, spectroscopic studies of EROs have not been so accumulated yet which can reveal unambiguously the redshift of EROs thus determine whether EROs are really dusty starburst galaxies or such high redshift red elliptical galaxies as have been recently discovered by the VLT (Benítez et al. 1998). Future extensive spectrophotometric studies which can reveal whether the extremely red colors of EROs result from dust effects or from galaxy aging will determine the relative importance of major galaxy merging in the formation of high redshift EROs.

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Fig. 1.— Upper panel shows the time evolution of star formation rate of a dusty gas-rich major galaxy merger at  $z=1.0$ . The star formation rate of the merger becomes maximum ( $\sim 378M_{\odot}/\text{yr}$ ) at the time  $T = 1.3$  Gyr. Lower panel shows the rest-frame SED of the galaxy merger at  $T = 1.25$  (dotted line),  $T = 1.3$  (thick solid), and  $T = 1.35$  Gyr (dashed). For comparison, the SED of the merger without dust extinction and re-emission is also given by thin solid line. Note that the far-infrared flux of the merger rapidly increases between  $T = 1.25$  and  $T = 1.3$  Gyr and decreases between  $T = 1.3$  and  $T = 1.35$  Gyr. Furthermore we can clearly see the effects of dust extinction and re-emission on the SED shape in the merger at  $T = 1.3$  Gyr by comparing the thick solid line and the thin solid one. In this figure, the observed SED of Arp 220 by Rigopoulou, Lawrence, & Rowan-Robinson (1996) is also given by a thin solid line with open squares. The reason for our failure to reproduce the observed SED around  $10^5\text{\AA}$  is essentially that we do not include the effects of small grains in the present study.

Fig. 2.— Mass distribution of a galaxy merger at  $T = 1.3$  Gyr corresponding to the epoch of maximum secondary starburst of the merger for total components (upper left), old stellar components initially located in two disks (upper right), gaseous ones (lower left), and new stellar ones formed by secondary starburst (lower right). Each of the four frames measures 64.4 kpc on a side.

Fig. 3.— The synthesized image of a galaxy merger at the redshift  $z=0.4$ ,  $1.0$ , and  $1.5$  projected onto the  $x - y$  plane corresponding to the orbital plane of the merger for the HST WFPC2 (upper four panels) and the HST NIC2 (lower four panels). Here the morphology of the merger at the epoch of the maximum starburst ( $T = 1.3$  Gyr) is described. The redshift of the merger is indicated in the upper right-hand corner of each panel and a bar with the length of 10 kpc is superimposed in the lower right-hand corner. Except for the extreme right panel, the exposure time for each synthesized morphology is set to be  $10^4$

sec ( $2000\text{sec} \times 5$ ) both for the HST WFPC2 and the HST NIC2. The exposure time of the synthesized optical and near-infrared morphology of the merger in the extreme right panel is  $1.24 \times 10^5$  sec ( $2000\text{sec} \times 62$ ) corresponding to that of the Hubble Deep Field (HDF). The filter adopted in the present study is F814W for the WFPC2 and F160W for the NIC2. Each frame measures  $9.''9$  on a side and one pixel size is  $0.''1$  for the WFPC2 and  $0.''076$  for the NIC2. The raw image is convolved with a WFPC2 point-spread function (PSF) generated by Tiny Tim ver-4.4 (Krist & Hook 1997) and the STSDAS FCONVOLVE task to convolve the PSF is used. A magnitude zero point is 21.60 mag for the WFPC2 (Holtzman et al. 1995) and 25.68 mag for the NIC2 (MacKenty et al. 1997). We assume that a sky surface brightness at  $V$  band is  $22.9 \text{ mag/arcsec}^2$  corresponding to  $0.054 e^-/\text{pixel}/\text{sec}$  (Biretta 1996). Readout noise, gain, dark noise are set to be 5.2 (35)  $e^-/\text{pixel}/\text{readout}$ , 7.0 (5.4)  $e^-/\text{DN}$ , and 0.005 (0.05)  $e^-/\text{sec}$ , respectively, for the HST WFPC2 (the HST NIC2). We adopted these values, based on the WFPC2 Instrumental hand book ver-4.0 (Biretta 1996) and HST NICMOS handbook (MacKenty et al. 1997). We used the NKNOISE package in IRAF in order to add noise to the images. We did not consider other noise sources such as cosmic rays and image anomaly in the present study.